ISS
Innovative Systems Software

Regional Workshop on

Evaluation of Specific Preventative and Mitigative Accident Management Strategies

ANALYSIS TOOLS AND PRINCIPLES OF APPLICATION

Presented Dr. Chris Allison

Outline

- General types of analysis tools
  - Simplified fast-running integral codes
  - Detailed specialized codes
    - RCS systems analysis
    - Containment
    - Other
  - Detailed integral specialized code packages
- Primary differences between more simplified integral codes and detailed specialized codes
  - Example – RELAP/SCDAP vs MAAP/MELCOR
- Implications for SA mitigation and management

Integral codes typically describe overall RCS and containment

- Most widely used integral codes
  - MAAP (EPRI)
  - MELCOR (USNRC)
  - ASTEC (EU – IRSN/GRS)
- Use simplified models in conjunction with extensive user options to allow realistic run times
- (See additional references on CD for more detailed descriptions)

Detailed specialized codes typically focus on RCS, containment, or source term

- System TH codes focus on RCS behavior during SA, ie.
  - – ICARE/CATHARE (IRSN)
  - – ATHLET-CD (GRS)
  - – RELAP/SCDAP (NRC/DOE/ISS)
- Two types of containment codes
  - – Lumped parameter, ie. – CONTAIN (NRC), COCOSYS(GRS)
  - – Multi-D CFD

Integral detailed specialized code packages

- SAMPSON (NUPEC) combines detailed specialized modules for integral calculations
- Other detailed codes are temporary linked for integral calculations, ie
  - RELAP/SCDAP – CONTAIN - VICTORIA
  - ATHLET-CD – COCOSYS
- See references on CD

Primary differences between specialized code packages and more simplified integral codes

- Specialized code packages (disadvantages)
  - Must be linked for integral calculations (excluding SAMPSON)
  - Computation times longer
- Specialized code packages (advantages)
  - Models are much more detailed (typIcally 2D/3D)
  - Typically used to support experimental programs
    - Validation is simplified
  - User options typically are limited
    - User influence limited
    - Input models typically easier to set up and qualify
  - Packages can typically be adapted more easily to different reactor system designs
    - Integral codes may be hardwired for reactor system design

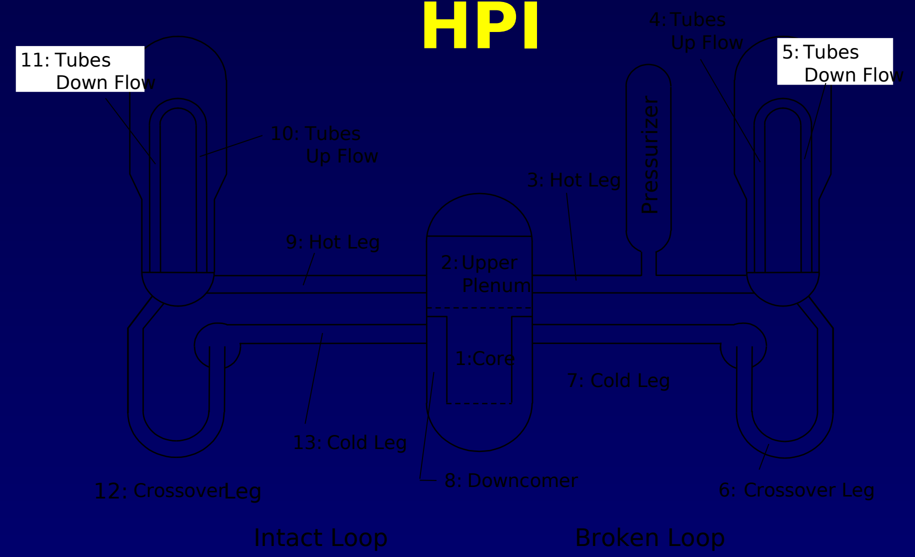
Example

RELAP/SCDAP VS MAAP/MELCOR

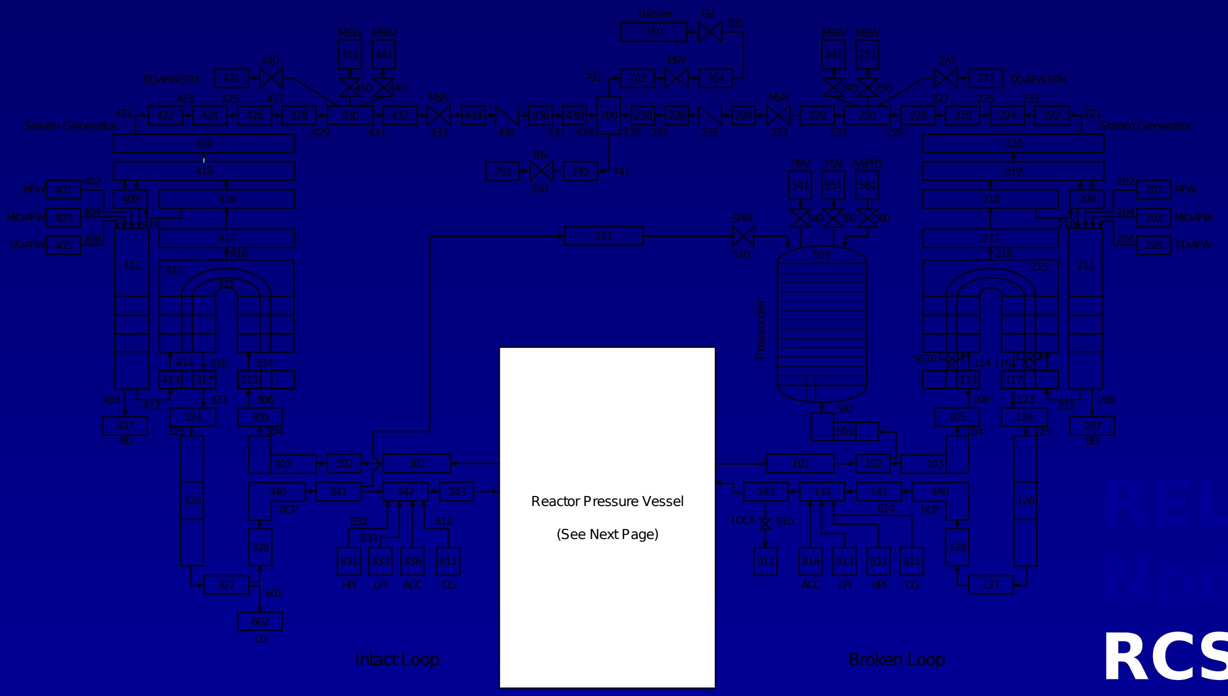
RELAP/SCDAP allows much more detailed representation of RCS/vessel

- RCS/Vessel nodalization more detailed than historical DBA analysis using RELAP/TRAC
  - 2D/3D core/vessel
  - 2D lower plenum/vessel
  - Detailed 2D core component modeling
- Typical SA input models use
  - Several hundred TH volumes and RCS heat structures
  - Five representative assemblies with 2 or more SCDAP components
  - Several hundred volumes in 2D lower plenum/vessel mesh

TML with AM and HPI

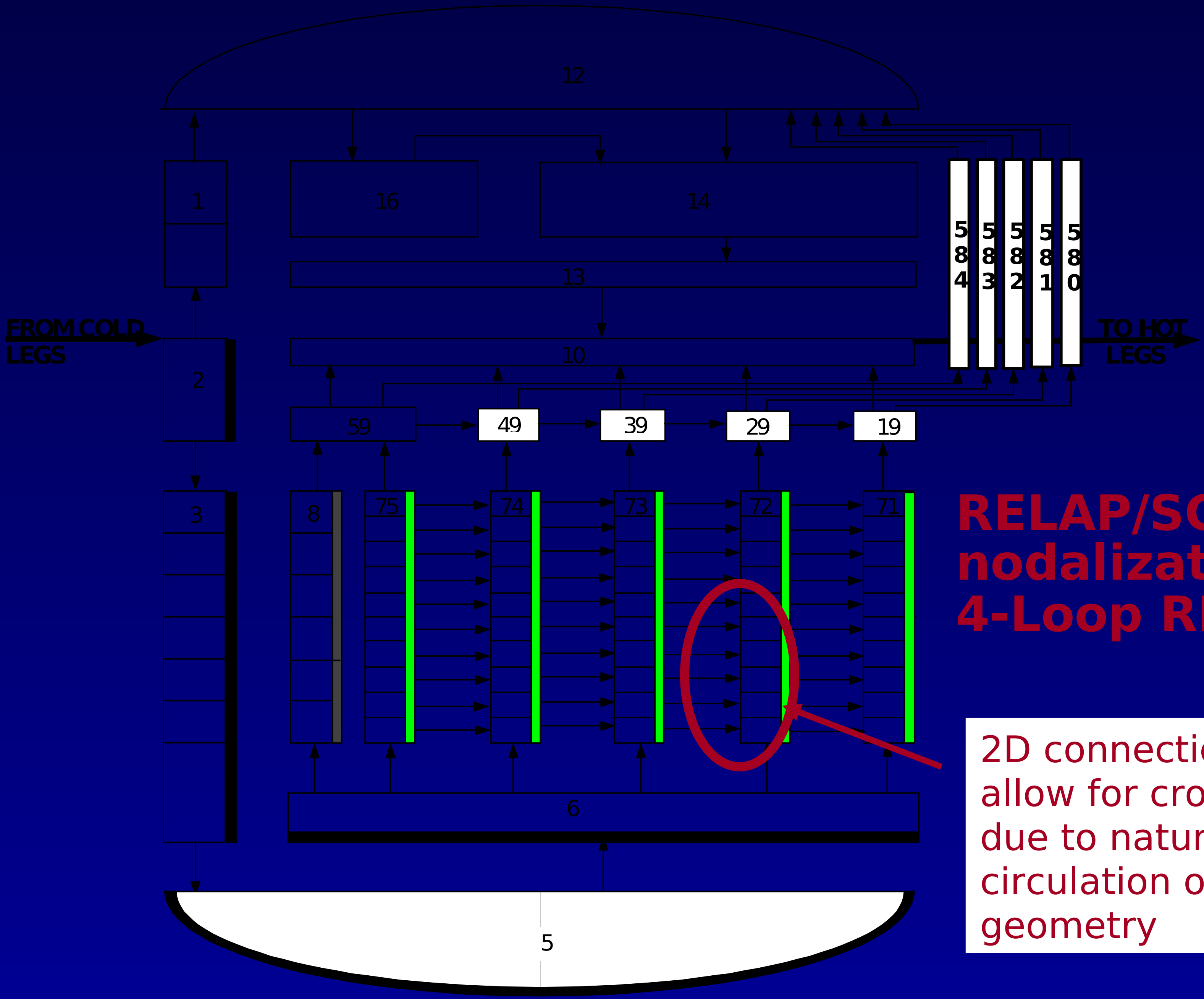


MAAP4 Nodalization of RCS



RELAP/SCDAP Nodalization of RCS

RELAP/SCDAP nodalization of 4-Loop RPV



2D connections allow for cross flow due to natural circulation or loss of geometry

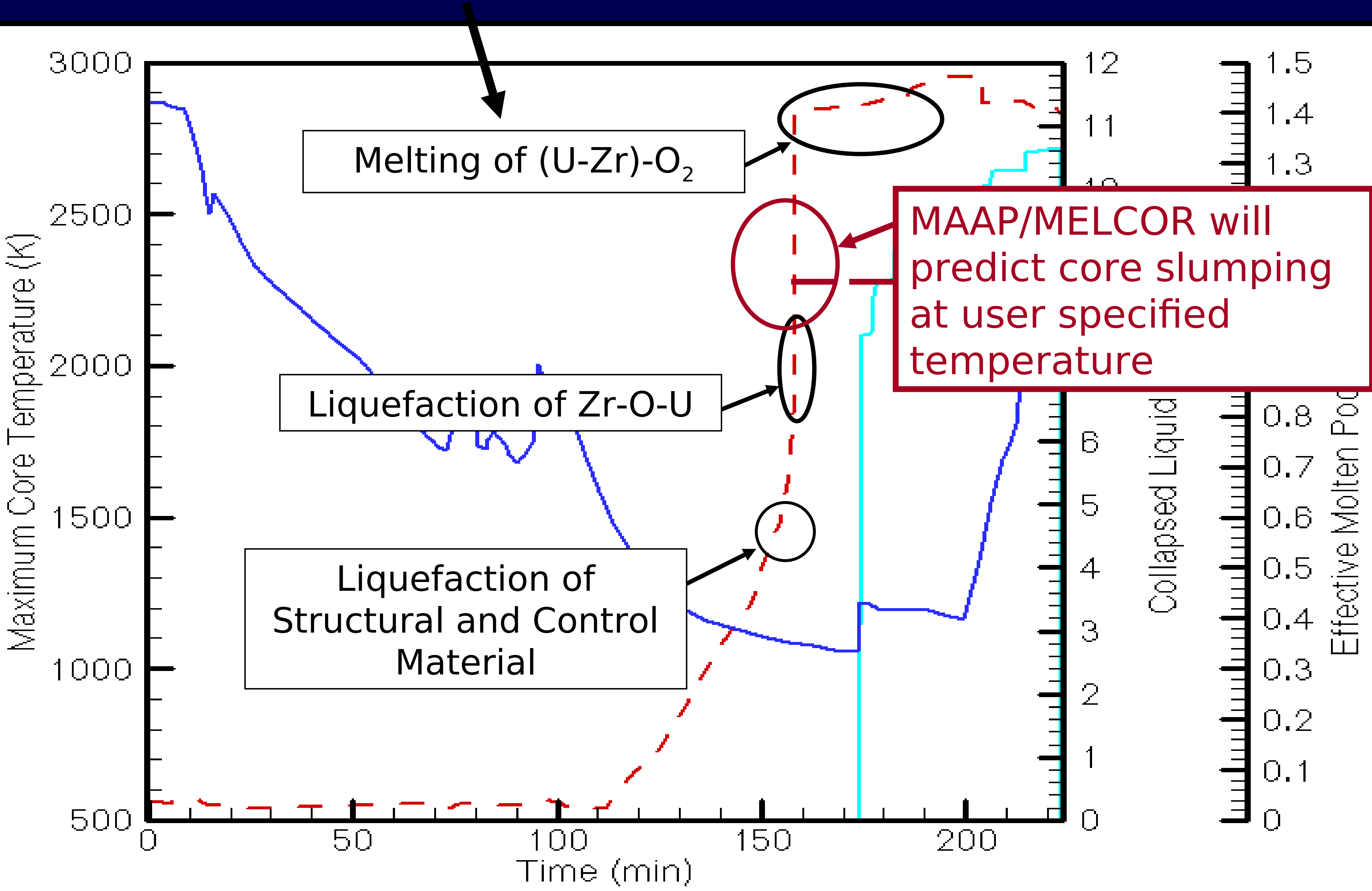
RELAP/SCDAP models generally more detailed

RELAP/SCDAP VS **MAAP/MELCOR**

- 6 equation, non-equilibrium hydro
- 2 D heat conduction
- Relocation of Zr-In, Zr-U-O, (U-Zr)-O2
- Grid spacer interactions
- Molten pool (U-Zr)-O2 formation, growth, and relocation
  - Radial, axial (bypass lower metallic layers)

- quasi-equilibrium hydrodynamics
- 1D lumped parameter
- Relocation of Zr-U-O
  -
  -
- Core slumping (user defined temperature)
  - Axial
  - User defined (MAAP)

SCDAP will predict melting over wide range of temperatures



Melting of (U-Zr)-O_2

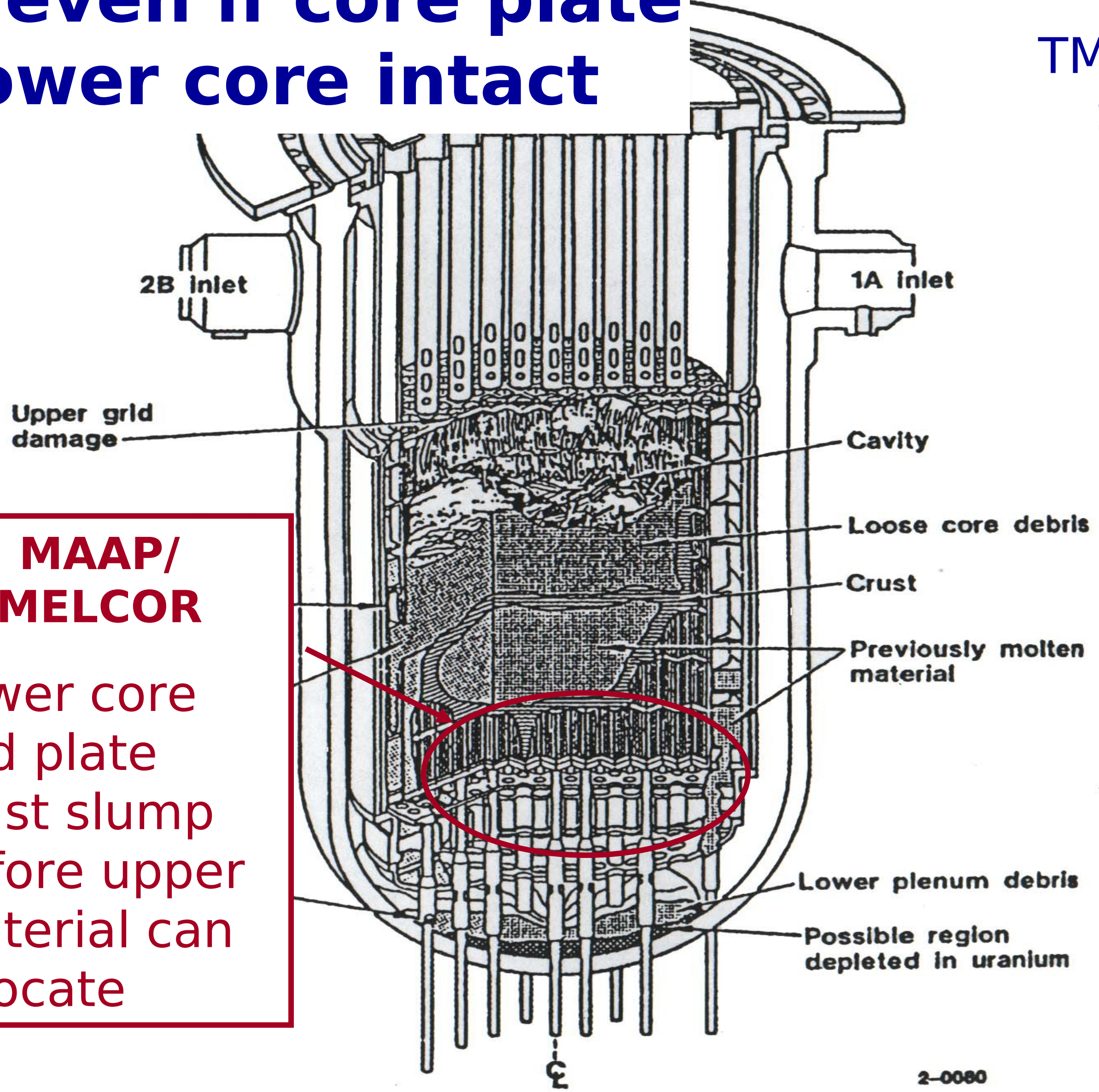
MAAP/MELCOR will predict core slumping at user specified temperature

Liquefaction of Zr-O-U

Liquefaction of Structural and Control Material

SCDAP can predict molten pool relocation into lower plenum even if core plate and lower core intact

TMI-2 End State



MAAP/ MELCOR

Lower core and plate must slump before upper material can relocate

RELAP/SCDAP models generally more detailed

RELAP/SCDAP VS **MAAP/MELCOR**

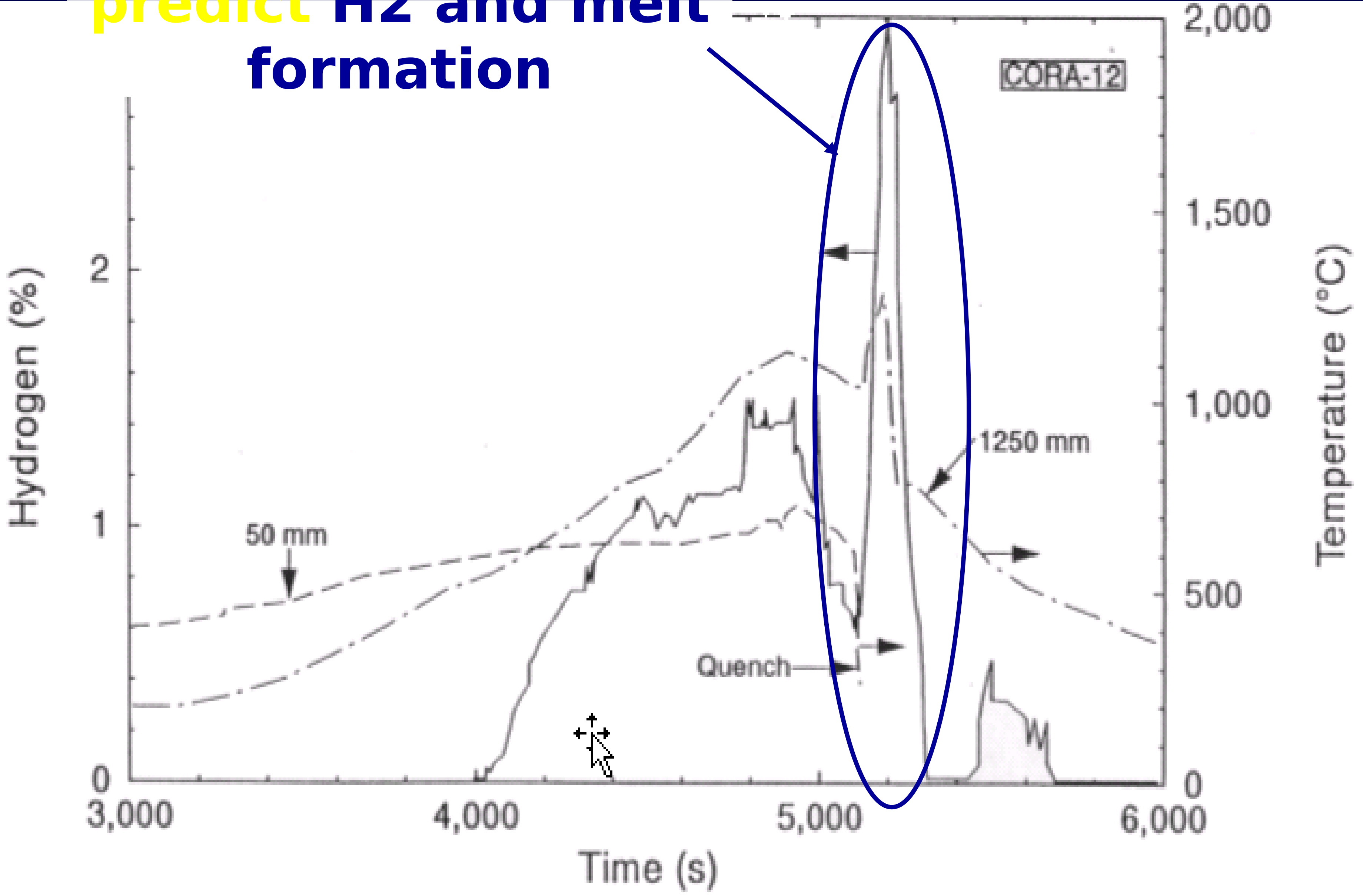
RELAP/SCDAP

- Reflood
  - Oxide spalling
    - Accelerated heating, oxidation, melting

MAAP/MELCOR

- Reflood
  - Oxide spalling (MELCOR)
    - Accelerated heating, oxidation, melting
  - MAAP does not consider oxide spalling

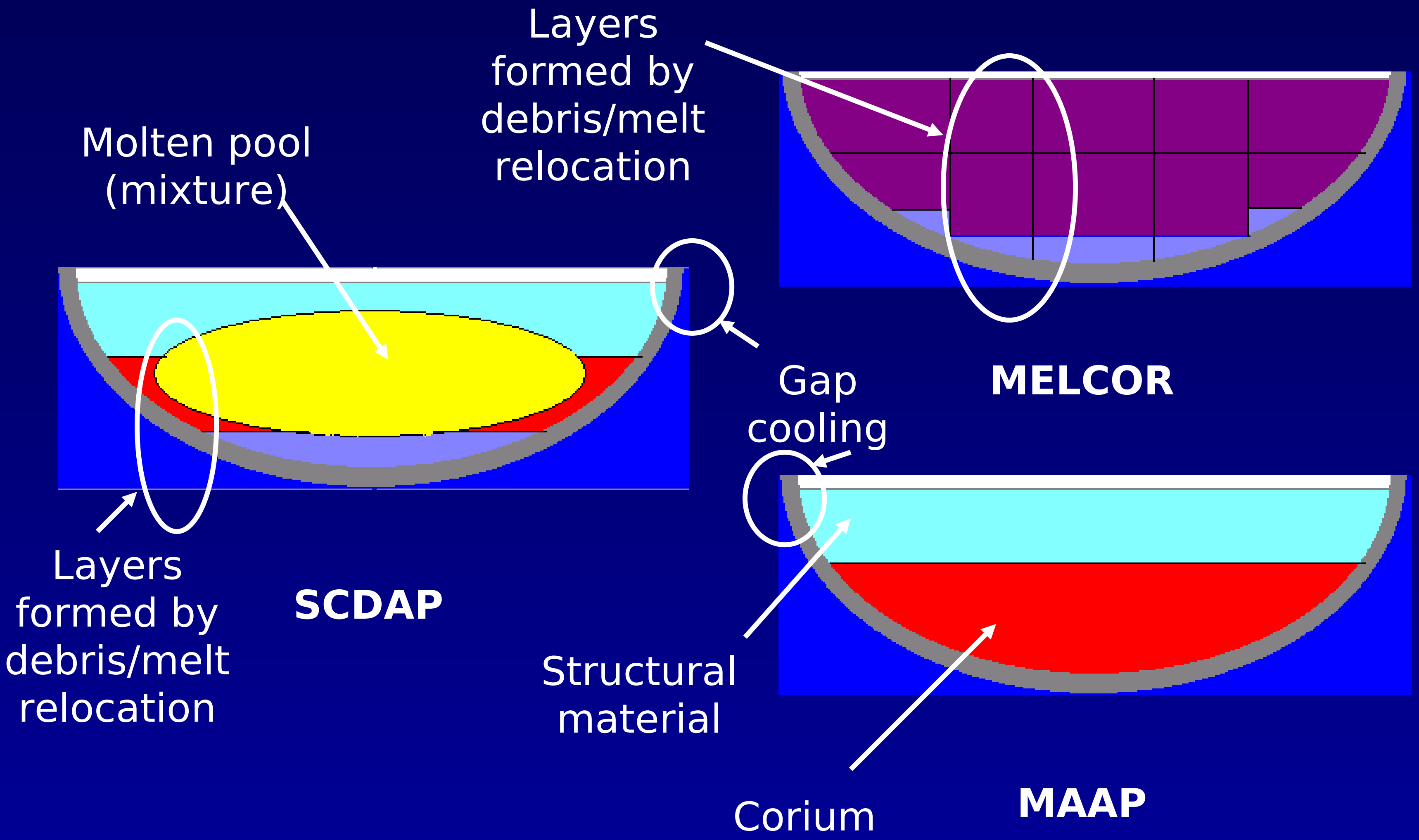
Oxide spalling during reflood critical to predict H2 and melt formation



RELAP/SCDAP models generally more detailed

RELAP/SCDAP	**vs**	**MAAP/MELCOR**
• Reflood		• Reflood
– Debris formation		– Debris formation (user)
– Exterior cooling of molten pool crusts		– Exterior cooling of debris beds (user)
• Transient 2D lower plenum debris/vessel heat conduction and molten pool convection		• Steady state analytic/lumped parameter lower plenum debris/vessel
– Stratified formation		– Stratified formation
– Homogenous molten pool		– Stratified metallic/ceramic (MAAP)

Assumptions on lower plenum debris will impact vessel failure



Molten pool (mixture)

Layers formed by debris/melt relocation

Gap cooling

MELCOR

Layers formed by debris/melt relocation

SCDAP

Structural material

Corium

MAAP

RELAP/SCDAP user defined parameters are intentionally limited

- System defined through TH nodalization, selection of representative core and plenum components and nodalization
  - RELAP5 and SCDAP user guidelines and training
- RELAP5 modeling parameters used to control flow regimes
  - Established through RELAP5 validation activities
- SCDAP modeling parameters limited to critical areas of modeling uncertainties
  - Recommended defaults set through validation activities

MAAP/MELCOR make extensive use of modeling parameters to adjust basic processes

- Extensive use of user defined parameters make evaluation of trends very difficult
- Scaling of code-to-data comparison results to plant behavior is unclear
  - Modeling parameters are unique to facility
  - Conservatism or non-conservatism may be influenced by user choices

Implications for SA mitigation and management

- Fast running integral codes invaluable to scope range of accident consequences and possible management strategies
- Detailed codes should be used
  - Benchmark integral calculations for representative transients
  - Extrapolate experimental results to plant response
  - Quantify system response for important SA sequences
  - Evaluate mitigation and management strategies

Implications for SA mitigation and management (cont)

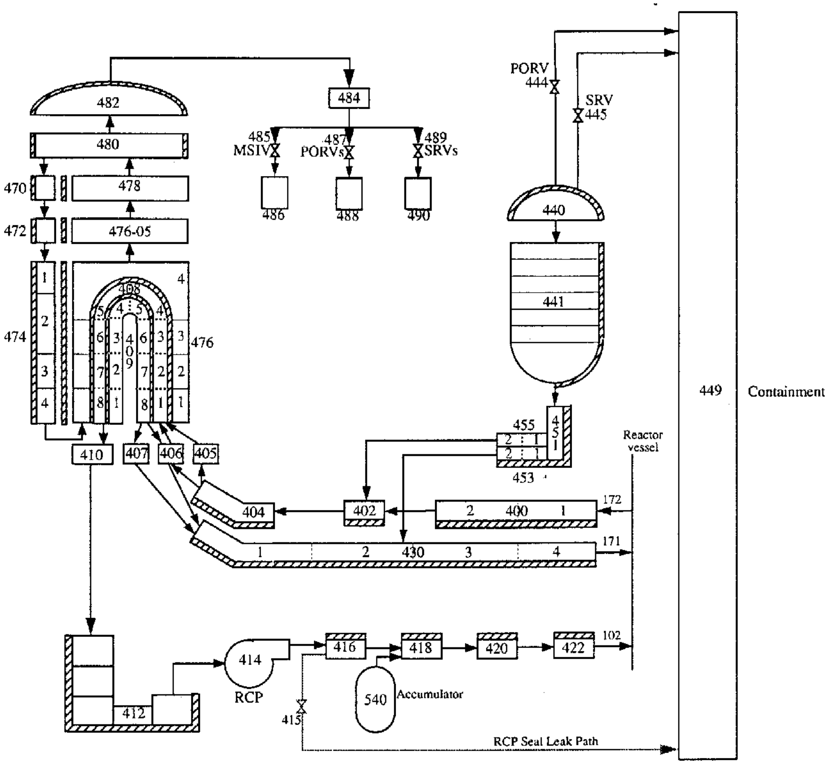
- Detailed system thermal-hydraulic codes should be used to determine RCS TH response during initiating and management phases
  - Inaccurate predictions for plant TH response will impact SA predictions
  - Reflood of hot damaged cores not adequately described by some simplified models

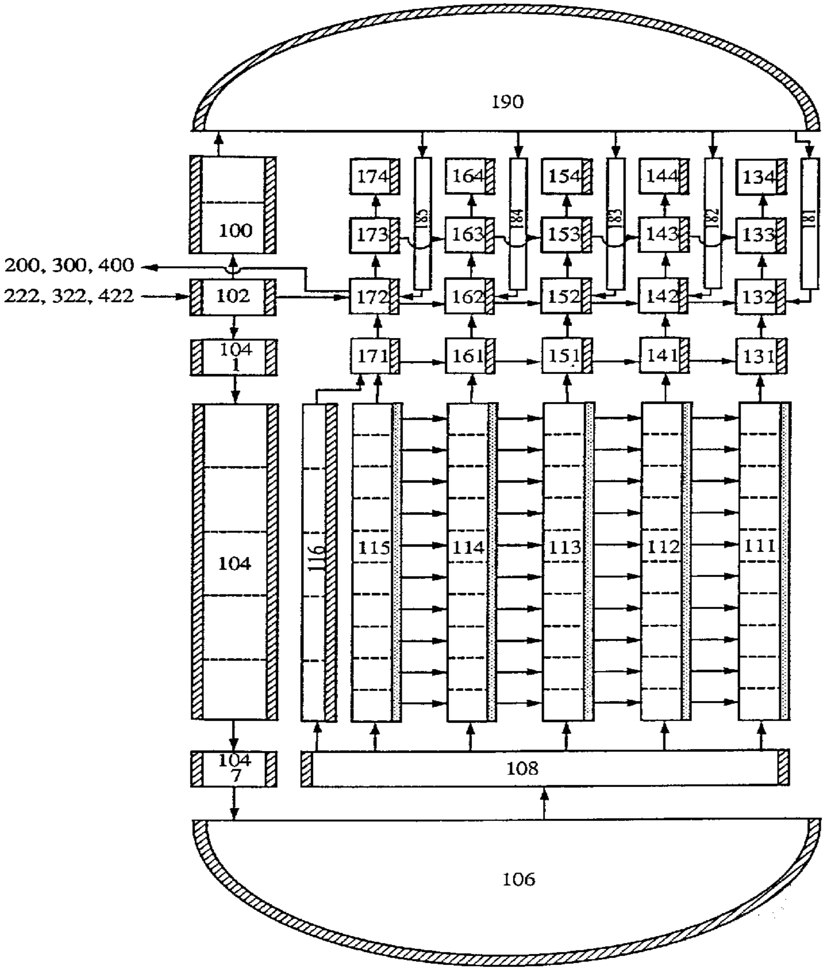
Example - Inaccurate predictions of plant TH response may dominate progression of accident

- Integral codes typically ignore influence of fuel rod ballooning and early loss of geometry on flow
  - Flow diversions, particularly in channel reactor designs, can result in non-coherent damage progression
    - Lower power/cooler channels are protected by flow diversion
    - Flow diversion can minimize hydrogen production and (potentially) early FP release
- Integral codes typically ignore or use “hard-wired” natural circulation patterns
  - Older versions ignored natural circulation in core/vessel
  - Some codes ignore “hot leg” circulation
- Integral codes may use simplified break flow models
  - Inaccurate break flow calculations directly impact prediction of core uncovery and start of heatup

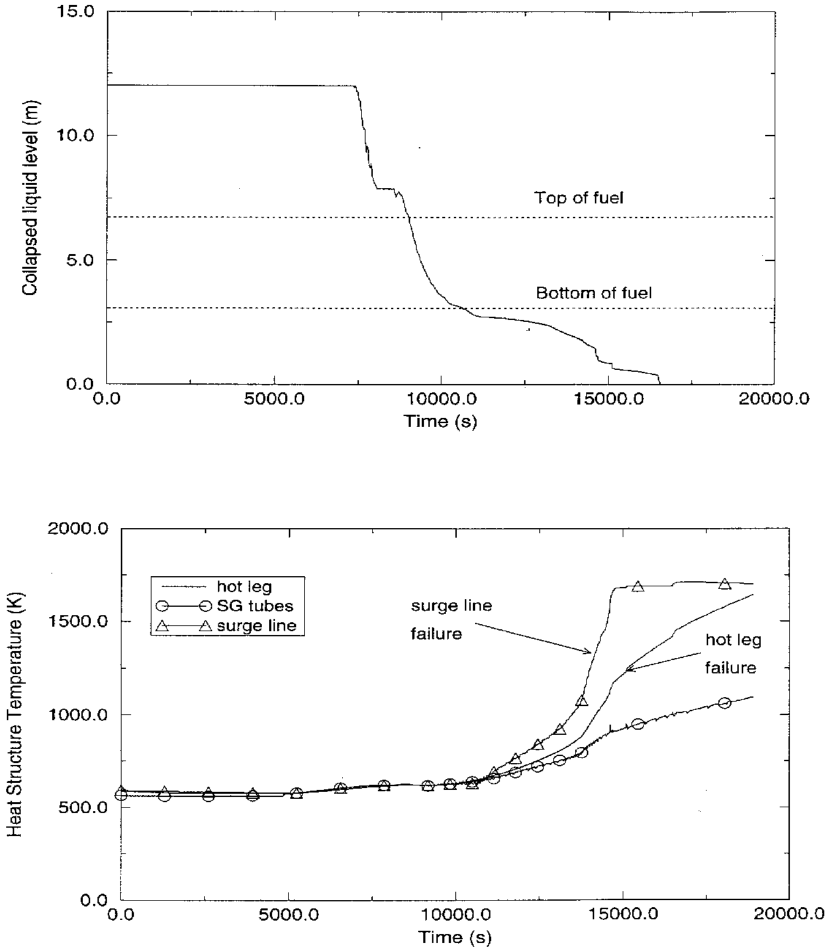
Example – Detailed RELAP/SCDAP system TH calculations helped minimize DCH or SGR as dominant risk contributors

- Surry SBO with hot leg natural circulation

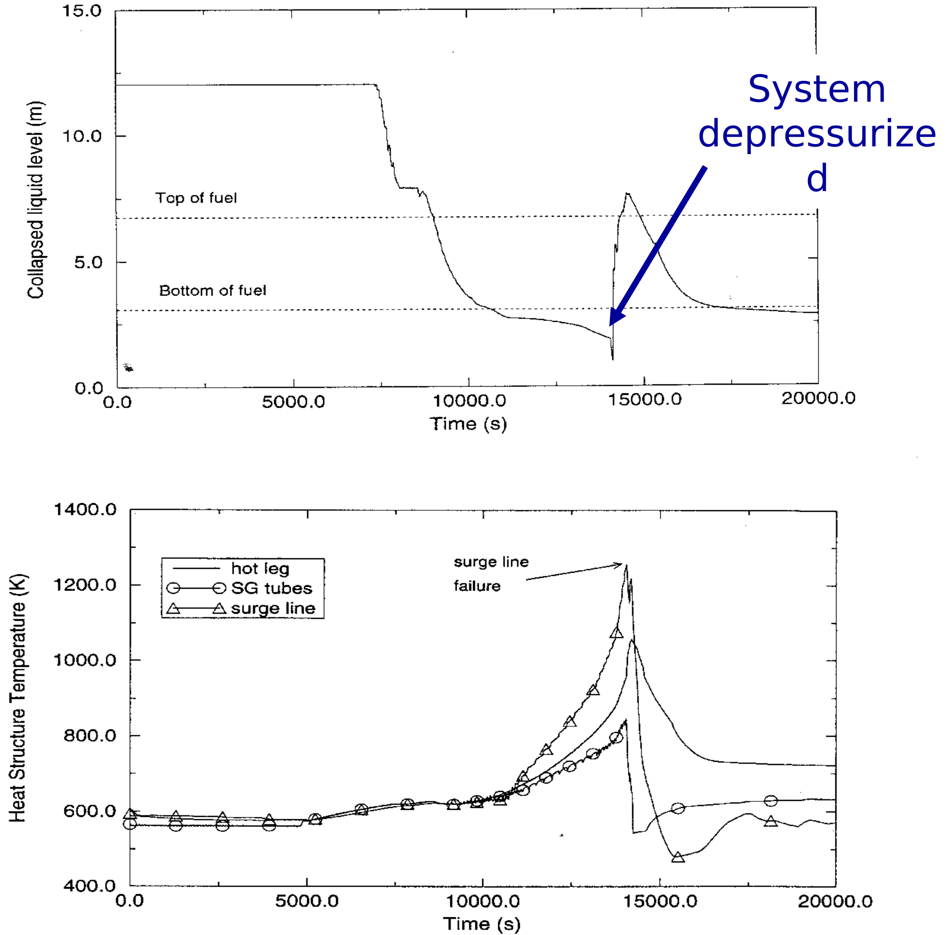




Example – Detailed RELAP/SCDAP system TH calculations helped minimize DCH or SGR as dominant risk contributors



Failure ignored in TH



System depressurized

Failure considered in TH

Implications for SA mitigation and management (cont)

- **Integral calculations** - Bounding calculations should be used for core liquefaction and slumping
  - Set model options based on applicable experiments OR
  - Set model options based on detailed model benchmarking
- **Detailed calculations** – Use model defaults with limited sensitivity studies to evaluate uncertainties

Example - Early failure of control materials at 1500 - 1700 K

- Early failure of control structures cause segregation of control and fuel materials
- Early failure of B4C control structures may limit negative impact of oxidation of B4C
  - Core heating and release of combustible gases to containment

Example - Early failure of control materials at 1500 - 1700 K (cont)

- **Integral calculations** - Options for separate modeling of control materials should used where available
  - Influence of B4C oxidation should be considered separately if modeling option not available
  - Influence of early metallic blockage formation should be considered
- **Detailed calculations** – Use model defaults unless developers recommend otherwise

Example - Melting and relocation of Zircaloy at 2100-2500 K can impact fission product release, blockage formation and hydrogen production

- Timing and temperature of molten Zircaloy relocation dependent on initial heatup and oxidation
  - Rapid heating (>0.5 K/s) or steam starved conditions can lead to early relocation
  - Slow heating (<0.3 K/s) in steam rich environment can delay or prevent relocation

Example - Melting and relocation of Zircaloy at 2100-2500 K …

- Dissolution of fuel by molten zircaloy may reduce fission product release relative to CORSOR-like correlations
  - Enhanced fuel dissolution can occur at intermediate heating rates (0.3 K/s - 1.0 K/s)
- Dissolution of fuel may lead to increased blockage formation
  - Molten zircaloy cladding can theoretically dissolve all of the fuel

Example - Melting and relocation of Zircaloy at 2100-2500 K …

- **Integral calculations** – Perform bounding study using Zr melting temperature for core slumping temperature
  - Use options to simulate metallic blockage formation where available
  - Use defaults or recommendations for UO2 dissolution
- Impact
  - Early relocation may accelerate slumping into lower plenum and vessel failure
  - Early relocation results in underprediction of hydrogen production, peak core temperatures (and stored energy) and lower-volatile fission product release

Example - Melting and relocation of Zircaloy at 2100-2500 K …

- **Detailed codes** – Use defaults or developer recommendations
  - Detailed models track relocation of metallic U-Zr-O

Example - Melting and relocation of UO2 and ZrO2 at 2900-3000 K can impact fission product release, blockage formation and slumping of core material into lower plenum

- The melting and relocation of the UO2 and ZrO2 dependent on irradiation history and initial heatup and oxidation
  - Fuel pellets mechanically stabilized by penetration of molten Zr into cracks and pellet interfaces

Example - Melting and relocation of UO2 and ZrO2 at 2900-3000 K …

- The melting and relocation of the UO2 and ZrO2 dependent on irradiation history and initial heatup and oxidation (continued)
  - Irradiated fuel can swell as the fuel approaches UO2 melting temperatures
  - UO2 and ZrO2 eutectic formation results in fuel slumping below melting point

Example - Melting and relocation of UO_2 and ZrO_2 at 2900-3000 K …

- The formation of stable crusts of $(U\text{-}Zr)\text{-}O_2$ promotes blockage formation and the radial growth of molten pools
- Natural circulation in the molten pools promotes the radial growth of molten pools

Example - Melting and relocation of UO2 and ZrO2 at 2900-3000 K …

- **Integral calculations** – Perform bounding study
  - Core slumping temperatures to 2900K
  - Fuel dissolution and blockages set to maximum
- Impact
  - Stored energy, peak core temperatures, non-volatile FP release should be more accurately predicted
  - Hydrogen production and volatile FP release may be overpredicted
  - Metallic blockage formation and early flow diversion will be ignored

Example - Melting and relocation of UO2 and ZrO2 at 2900-3000 K …

- **Detailed calculations** – Use model defaults or developer recommendations
  - Fuel rod and molten pool models track the melting of UO2 and ZrO2 and formation, growth, and slumping separately from the U-Zr-O

Implications for SA mitigation and management (cont)

- **Integral calculations** – Some integral codes or older versions may not be appropriate to predict influence of core/vessel reflood
  - Models or options not available to treat influence of coupled oxidation (accelerated heating and melting) or blockage formation
    - Review Quench ISP and Quench related research activities
  - Where available turn on reflood oxidation and molten pool options
  - Set model options based on applicable experiments OR detailed model benchmarking
- **Detailed calculations** – Use model defaults or recommendations
    - Review Quench ISP and Quench related research activities

Example - The impact of vessel flooding strongly dependent on temperature and state of the core and debris

- Fuel rods with heavily oxidized Zircaloy may quench and break up, forming loose debris of fuel and ZrO2
- Regions of metallic blockages of control, structural, and unoxidized Zircaloy may slowly cool and be relatively unchanged in geometry

Example - The impact of vessel flooding ...

- Regions of core with unoxidized Zircaloy at 1500-2300 K can experience dramatic increases in hydrogen production, temperature, and the formation of melts prior to quenching
- Ceramic molten pools may stabilize, continue to grow, or may partially slump
  - depending on the cooling and mechanical stability of the ceramic crusts

Example - The impact of vessel flooding ...

- Regions of debris in the lower plenum and vessel walls may cool or continue to heat up depending on
  - particle sizes and porosity of the debris
  - mechanical stability of the debris (formation of cracks)
  - shrinkage of the debris or vessel wall deformation to form gaps

Example - The impact of vessel flooding …

- **Integral calculations** - Predicted results will depend very much on code (and in some cases code version used)
  - Early versions of MELCOR do not have models or options to treat influence of oxidation during reflood(accelerated heating and melting) or molten pool formation
  - Standard version of MAAP does not have models to treat influence of oxidation during reflood

Example - The impact of vessel flooding …

- **Detailed calculations** – Widely used codes have detailed models to treat the influence of coupled oxidation, blockage formation and TH
  - Use defaults or developer recommended options

Implications for SA mitigation and management for VVERS/RBMKS

- Important trends of core damage progression well understood
  - Surprises may still occur for VVER/RBMK designs and materials
- Robustness of mitigation and management strategies will strongly depend on the codes/models used
  - Select the appropriate codes or models
  - Select options for appropriate material properties or incorporate appropriate properties
  - Review relevant experimental results
  - Participate in ongoing code development and validation activities

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